

Wide Angle Light Scattering In Shock-Laser Interaction

J. Panda*

University of Toledo, Toledo, Ohio

Introduction

Any change of gas density in a flow field is accompanied by a change in the refractive index. The sharpest change is found in a shock wave which has a very small thickness. Light disturbances propagating across this sharp change deviate from their original path and make the shock easily visible in schlieren and shadowgraph images¹. The net change in the index across even a strong shock is very small, and therefore, the angular deflection of the light rays are also small (Kriksunov and Pliev²). In this paper an optical phenomenon is presented where a very wide angle scattering of light is observed due to interaction between a shock wave and a laser beam. The phenomenon is described in brief through figure 1 where a conical shock surface and a narrow laser beam are considered. The laser beam is moved to three different axial locations parallel to the axis of the cone. It is observed that the scattered light appears in the form of a sheet at location B, where the beam is tangent (i.e., at a grazing incidence) to the shock surface. When the beam is moved to the location C, where it pierces the shock surface the scattered light disappears. The photographic evidences, a detailed description and possible physical reasons behind this optical phenomenon are discussed in the text.

Experimental set-up

The present experiments were conducted in a free air jet facility³ at the NASA Lewis Research Center. High pressure air was exhausted through a 25.4 mm diameter (D) convergent nozzle to produce various underexpanded supersonic free jets. The pressure ratio (P_R = plenum pressure/ atmospheric pressure) was varied between 2.42 and 5.75 to obtain various degree of underexpansion. The shock structures formed in such jets were visualized by a standard schlieren system.

The green line (0.514 μm wavelength) of an Argon-ion laser, transmitted by a fiber-optic system was used for studying the scattering phenomenon. The diameter of the beam out of the optical fiber is about 2 mm which is then focused at the jet centerline to a diameter of 0.16 mm.

Figure 2 shows a schematic of the visualization set-up. The scattered light pattern was visualized on a semi-transparent screen, made of a piece of translucent graph paper. The screen was mounted parallel to and 280 mm away from the jet axis. It was found that the relatively weak scattered light was difficult to observe if the main laser beam was allowed to fall directly on the screen. Therefore, a 4.8 mm diameter hole was made in the screen to allow the main beam to go through. The light pattern on the semi-transparent screen was photographed by a 35 mm Nikon F4 camera, with a slow shutter speed of 1/15 to 1/8 second. The complete optical set-up was mounted on a 3-axis Klinger traversing unit which allowed it to be moved along the stream wise and the transverse directions.

Results

The shocks formed in an underexpanded jet of pressure ratio, $P_R = 3.18$ are shown in the schlieren image of figure 3(a). The 2-dimensional projection of the shock surfaces visible in this photograph is triangular, indicating conical surfaces in the actual axisymmetric flow field. Only the first shock surface is used to demonstrate the optical phenomenon. The locations of the laser beam with respect to this shock, for the photographs of figure 3(b), are also indicated. The beam is normal to the plane of the paper, and the laser power used is about 70 mW.

* Resident Research Associate, NASA Lewis Research Center, Cleveland, OH 44135
Member, AIAA

In photograph I, the laser beam is positioned upstream of the shock and any light scattering phenomenon is absent. In photographs II and III the beam is grazing the shock surface, respectively, at $z/D = -0.45$ and 0.3 ; where z is the radial coordinate. The normal cross-sections of the scattered light appear as bright streaks spreading out from the main laser beam in both upstream and downstream directions. The streaks are oriented along the normal to the shock surfaces which are also the direction of local refractive index gradient produced across a shock. Noticeably, the streaks are brighter in the downstream side of the shock. This indicates a stronger scattering in the higher density and higher refractive index side of a shock. The maximum visible value of the scattering angle, θ , defined as,

$$\theta = \tan^{-1} \left(\frac{\text{Distance on screen from center of the hole}}{\text{shock to screen distance}} \right), 1$$

and calculated from photograph II is about $\pm 5^\circ$. Both the intensity and the divergence angle of the scattered light are found to increase as the shock strength is increased. It should be noted that the scattered light appears only when the laser beam is placed along the triangular trace of the shock surface shown in figure 3(a). Along this trace, the laser beam is at a grazing incidence to the shock surface. At any other locations where there is no shock or the beam pierces through the conical shock the photograph of the screen is similar to that of I (figure 3b).

Figure 4 shows photographs similar to those of figure 3, but for a pressure ratio of 5.75. The appearance of the shock surface is very different; a Mach disk has formed, the barrel shock from the nozzle lip to the Mach disk is clearer, and there is a reflected shock from the tip of the Mach disk to the shear layer around the jet. Photographs I, II and III of figure 4b were obtained by placing the laser beam in three close positions across the Mach disk. For the latter two, the beam was moved downstream, respectively by, 0.3 mm and 0.6 mm from its position in photograph I. At location I the beam just touches the upstream side of the Mach disk and the streak pattern on the screen shows definite secondary maxima on both sides. Visual investigation revealed one more maximum further to the right beyond the width of the screen. The angular distance between the main beam and each of the secondary maxima, estimated from photograph I of figure 4(b), is quite large, about 12.5° . As the beam is moved further downstream, very slowly through the shock, the secondary maxima come closer to the beam forming a continuous streak shown in photograph II. The maximum value of the visible scattering angle is still very high, about $\pm 10^\circ$. In the photograph III, the Mach disk is just left of the laser beam, and the light streak on the upstream side of the shock is very weak. In the last photograph (IV) the beam was moved to a position where all three shock surfaces (the barrel shock, the Mach disk and the reflecting shock) merge. As expected, three intersecting streaks along directions normal to each of the shock surface are visible in this photograph.

The scattered light pattern is found to be independent of the polarization of the laser beam and is equally visible when the blue beam (wavelength = $.488 \mu\text{m}$) instead of the green ($.514 \mu\text{m}$) is used.

Discussion of possible physical reasons

Since the time of first observation various factors that may lead to light scattering were eliminated as possible reasons. The scattering phenomenon can not be caused by small particles as clean and dry air was used. Neither can it be attributed to the refractive index fluctuations caused by random turbulence, since the scattered light disappears just upstream or downstream of the shock. Another relevant concern is the effect of shock unsteadiness. The shock of figure 3 was oscillating by less than ± 1 mm about its mean position³. However, the resulting oscillation of the laser beam was too small to be detected, as the beam passed through the central hole on the screen independent of the appearance or disappearance of the scattered light. To determine the effect of shock unsteadiness, the light pattern on the screen was photographed by a light intensified CCD camera that was gated to a fast shutter speed of 100 nano-seconds. A frame by frame analysis showed that the streak patterns either appear completely or disappear completely at the oscillation frequency. The instantaneous patterns also resemble to those shown in figures 3 and 4.

To further analyze this phenomenon, various relevant parameters for the Mach disk of $P_R = 5.75$ jet (which corresponds to the photographs of figure 4) are estimated and shown in Table I. The calculation procedure is described in reference 3. The change in the refractive index even across the Mach disk, as shown in Table I, is small. The beam steering effect due to refraction of light across the shock is also expected to be a fraction of a degree as calculated by Kriksunov and Pliev² and measured by Faris and Byer⁴. However, the visible spread angle

of the scattered light associated with the present optical phenomenon is large, between $\pm 5^\circ$ to $\pm 12^\circ$ depending on the shock strength. Moreover, all of the above calculations show that the beam bends *along* the direction of refractive index gradient while, nearly half of the scattered light appears upstream of the shock which is *opposite* to such a direction created across a shock.

Neither of the above analysis considers the special situation of grazing incidence when the present optical phenomenon appears. In this condition, the shock appears as an interface parallel to the direction of propagation of the laser beam. Due to the extremely small shock thickness, the jump in refractive index is very sharp. The situation is somewhat analogous to shining a laser beam along the edge of a glass plate when a streak is observed in the far field due to diffraction of the laser by the index of refraction gradient. The streak patterns shown in the earlier figures support this analogy. Such streaks can be considered as the Fourier transform of the step function in the refractive index caused by the shock.

Light diffraction caused by the shock waves has been observed in the shadowgraph images by Pfifer *et al*⁵. (also see discussion in page 133, Merzkirch¹). A second way of looking at the diffraction phenomenon is as follows. At the grazing incidence, a part of the beam propagates upstream (lower refractive index) and the rest downstream (higher refractive index) of the shock. The difference in the optical path length between the two parts of the beam produces phase variation. Therefore, a shock wave effectively acts as a 'phase object'⁶ that distorts the phase distribution in the laser beam. The resulting diffraction pattern is believed to manifest as the long streaks seen in figures 3 and 4.

Reference

¹Merzkirch, W., *Flow Visualization*, Academic Press 1987, pp. 123.

²Kriksunov, L. Z. and Pliev, A. E., "Refraction of Laser Beams at a Compression Shock," *Sov. J. Opt. Technology*, Vol. 51, No. 7, July 1984. English Translation by The Optical Soc. of America, 1985.

³Panda, J., "Partial Spreading of a Laser Beam Into a Light Sheet By Shock Waves And Its Use As A Shock Detection Technique," NASA CR-195329, 1994.

⁴Faris, G. W. and Byer, R. L., "Three-Dimensional Beam-Deflection Tomography of a Supersonic Jet," *Applied Optics*, Vol. 27, No. 24, Dec. 1988, pp. 5202-5212.

⁵Pfeifer, H. J., Vom Stein, H. D. and Koch, B., "Mathematical and Experimental Analysis of Light Diffraction on Plane Shock Waves," *Proc. Int. Cong. High-Speed Photography*, 9th, 1970, pp. 423-426.

⁶Born, M. and Wolf, E., *Principles of Optics*, Sixth edition, Pergamon Press, 1989, pp. 425.

Table I. Estimated values of parameters relevant to the optical phenomenon observed in $P_R = 5.75$ jet (figure 4).

Parameter	Upstream of Mach disk	Downstream
Mach No.	3.25	0.46
Static pressure	10.8 KPa	496 KPa
Density	0.4 kg/m ³	1.63 kg/m ³
Refractive index	1.00009	1.00037
Shock thickness: between 0.37 μ m and 0.62 μ m		
Laser Wavelength: 0.514 μ m		

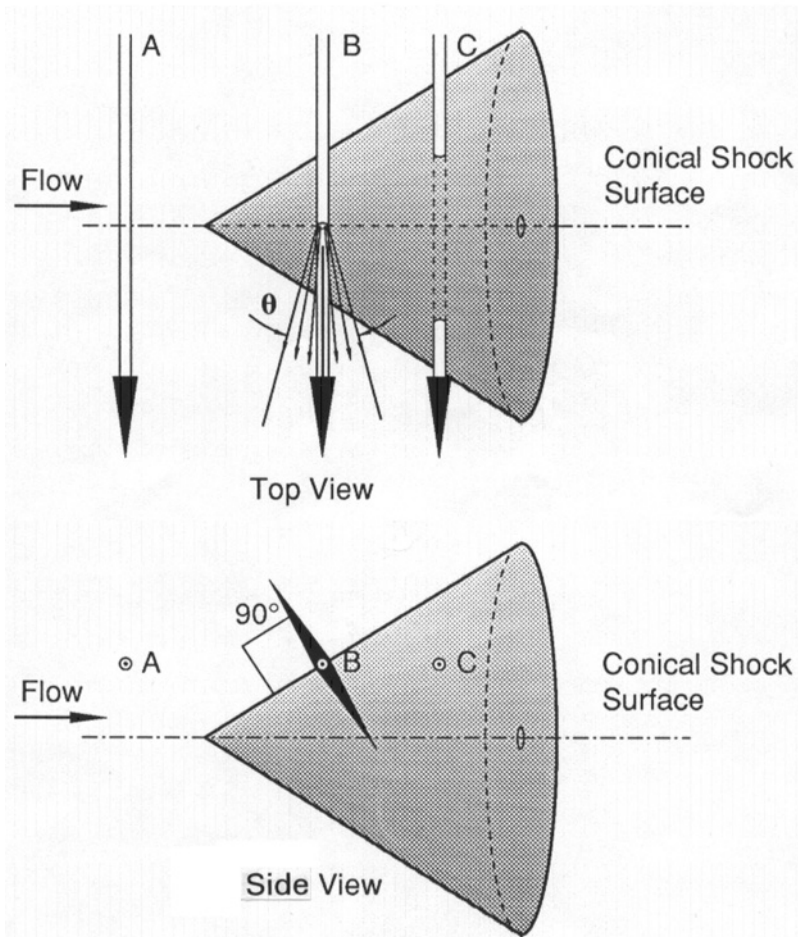


Fig. 1. Schematic of the optical phenomenon. A, B and C are different positions of the laser beam which is normal to the plane of the paper in the side view and parallel in the top view.

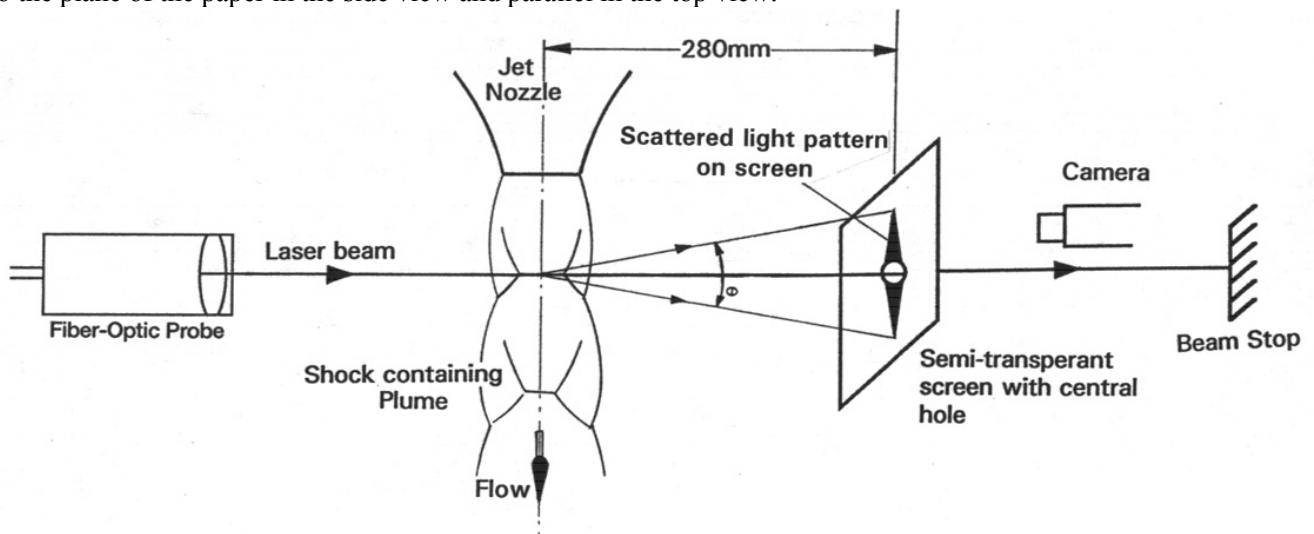


Fig. 2. Schematic of the arrangement to photograph the scattered light pattern.

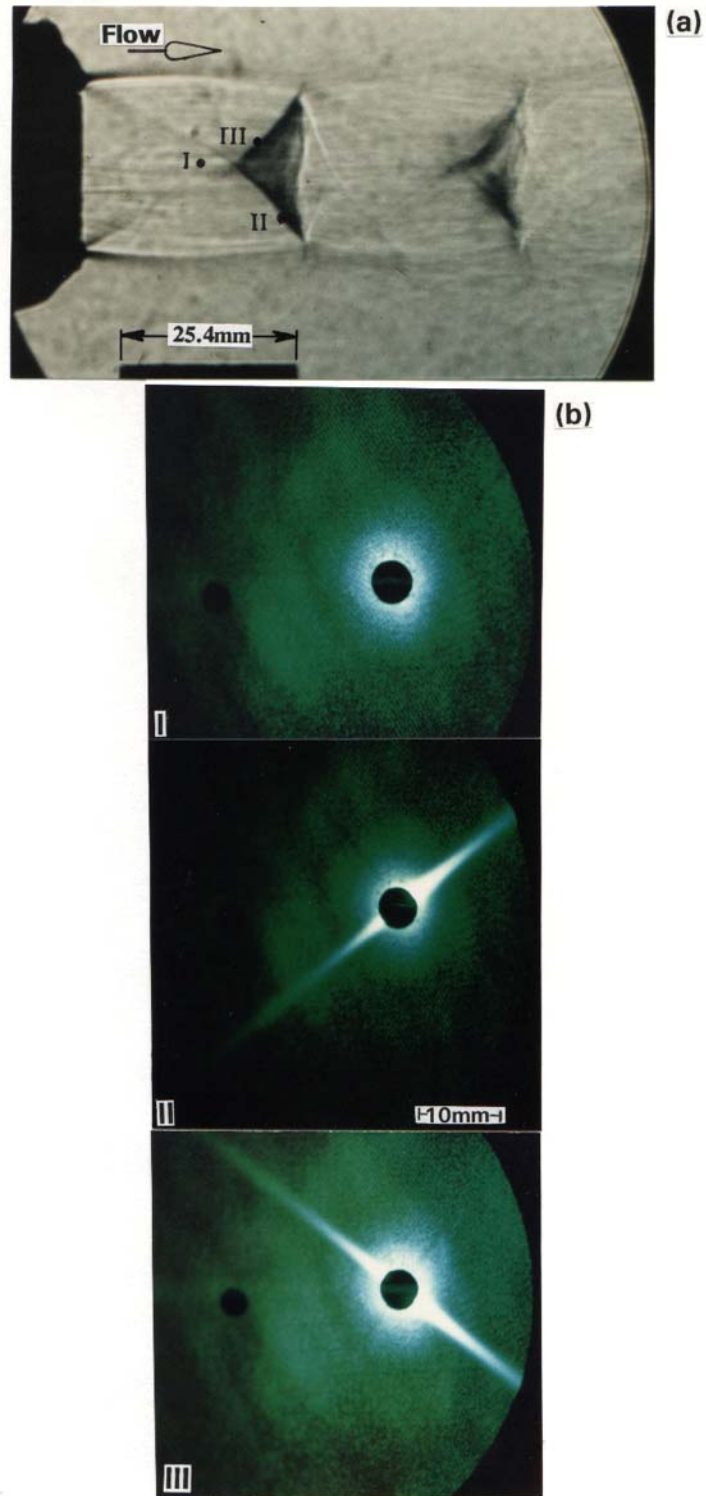


Fig. 3. (a) Schlieren photograph of pressure ratio $P_R = 3.18$ underexpanded jet and locations of the laser beam. (b) Scattered light pattern on the screen from indicated locations.

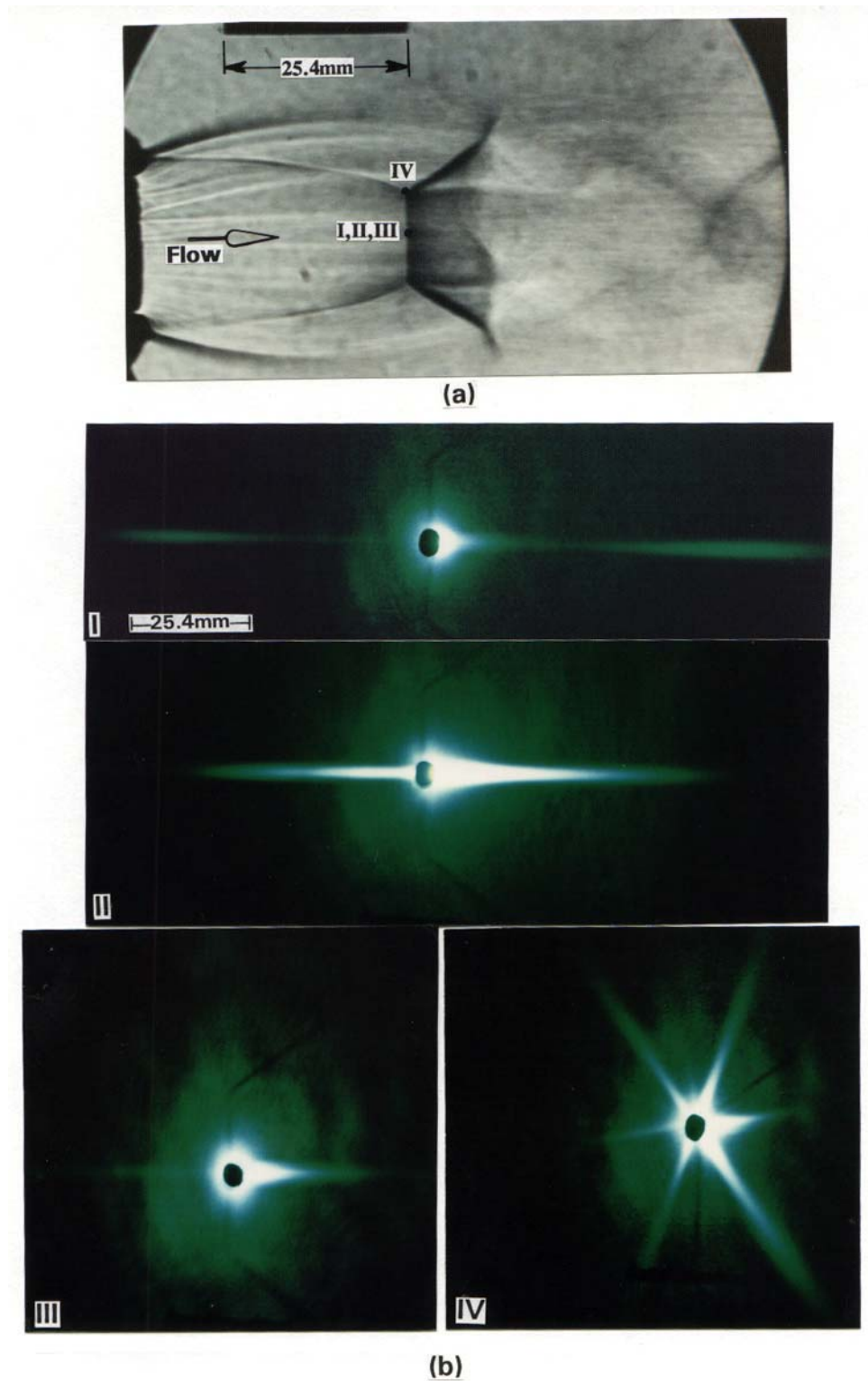


Fig. 4. (a) Schlieren photograph of $P_R = 5.75$ jet and locations of the laser beam. (b) Scattered light pattern on the screen from indicated locations.